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# THESIS

**DUNE EROSION, MEGA-CUSPS AND RIP CURRENTS: MODELING OF FIELD DATA**

by

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Sand dune erosion is highly episodic occurring only when storm waves coincide with high tides generating swash that impacts the toe of the dune. Owing to the episodic nature of sand dune erosion, it is difficult to observe in nature. The removal of a structure and rip-rap sea-wall from the Stilwell Hall site located in southern Monterey Bay provided a unique opportunity to study erosion processes at an accelerated rate. A 1-D wave impact line erosion model (Larson et al., 2004) was tested against data acquired at this site between April, 2004 and April 2005. The model was optimally tuned to the data by a dimensionless coefficient that relates the impact force to the rate of recession. The coefficient values ranged from $0.7\text{-}1.3\text{x}10^{-3}$, for this field data, compared with values of $1.0\text{-}2.5\text{x}10^{-3}$ previously obtained for lab and field data.

Migrating rip currents create a system of mega-cusps, which are nominally 10m in width and 200m in alongshore wavelength (Thornton, 2005). The presence of mega- cusps is hypothesized to accelerate sand dune erosion at their embayments where the beach is steeper and narrowest (Short, 1979; Shih and Komar, 1984; Revell, et al., 2002). It was determined that the highest recession occurred at the location of the rip current/mega-cusp embayment. Changes in the surf climate are of great interest to Naval Special Warfare (NSW) and U.S. Marine Corps (USMC) forces tasked with planning and executing operations in littoral areas. Naval history is replete with operations highlighting the importance of understanding and accurate prediction of nearshore dynamics. Without the ability to predict nearshore morphologic processes, providing such support is impossible.

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# DUNE EROSION, MEGA-CUSPS AND RIP CURRENTS: MODELING OF FIELD DATA


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# ABSTRACT

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# I. INTRODUCTION

The coastal topography of southern Monterey Bay (Figure 1) is dominated by sandy beaches and high dunes ranging in height from 5-40m. These features protect residential areas, critical roadways and commerce sites from elevated wave run-up during storm events. For various reasons, these beaches and dunes are receding at the relatively high rate of 0.5-2 m/yr (Thornton, et al., 2006), which is the highest rate in California. This erosion is episodic in nature, only occurring during times of coincident high tides and storm surf, which leads to swash impacting the face of the dune. This swash-induced erosion results in dune recession and is cause for serious concern among coastal planners and ecologists. Due to the relatively infrequent coincidence of exceptional high tides and storm surf, the erosion process, and subsequent beach and dune recession, have been difficult to accurately survey and analyze. Since this recession endangers the infrastructure surrounding southern Monterey Bay, it is crucial to gain a better understanding of this process and to develop a tool which can accurately predict its short and long term effects. To accomplish this goal, a dune erosion model is evaluated.

In March, 2004, Stilwell Hall, a structure which was located in southern Monterey Bay, was torn down after efforts to abate the local effects of dune recession grew increasingly unsuccessful. Stilwell Hall was built as an enlisted man’s club by the United States Army on Fort Ord in 1944. At that time, a football field fronted the building on its seaward side. Stilwell Hall enjoyed a commanding view of the Pacific Ocean owing to its picturesque location on the dunes (Figure 2), but due to dune recession the integrity of the structure became endangered. By 1978, the recession was significant enough to require construction of a rock-rubble sea-wall, which was further augmented in 1985. As the recession of the dune crest continued, passive erosion resulted in the formation of a peninsula extending into the water at the Stilwell site (Figure 3). After a large piece of the buildings foundation had to be removed before collapsing into the bay, and in light of the fact that the Army had officially closed fort Ord nearly ten years prior, it was determined that the structure should be demolished.

The demolition of Stilwell Hall and removal of the rock-rubble seawall in March, 2004 left a large sand peninsula (Figure 3) immediately exposed to the assailing wave energy. This created a unique opportunity to study dune erosion and the subsequent recession of the peninsula at a highly accelerated rate. The area was routinely surveyed since the removal of the seawall. Southern Monterey Bay beaches and dunes were surveyed in April 2004 using LIDAR imagery techniques that provides the initial volume of the dune. Seven beach surveys were conducted over the 2004-2005 winter, which was the period of greatest erosion, using a kinematic GPS system for the purpose of observing erosion processes and recession of the dune.

In addition to the effects of erosion on local infrastructure, beach topography affects the wave and surf climate in littoral regions. Storm-induced erosion sets up a feedback mechanism between surf zone dynamics and the coastal topography (Komar, 1998). The recession of sand dunes is driven almost exclusively by storm induced erosion events and alters the on-shore topography as well as the nearshore bathymetry. Changes in bathymetry and topography lead to fluctuation in the location and intensity of waves and currents in the surf zone (Woods, 2005; Komar, 1998). Changes in the surf climate are of great interest to Naval Special Warfare (NSW) and U.S. Marine Corps (USMC) forces tasked with planning and executing operations in littoral areas. Naval history is replete with operations highlighting the importance of understanding and accurate prediction of nearshore dynamics. Without the ability to predict nearshore morphologic processes, providing such support is impossible.

The wave dynamics in the vicinity of Monterey Bay are well understood and readily predicted using several currently available models (O'Reiley, 1993). Modeling erosion driven dune recession has proven more problematic owing primarily to large variability in size, shape, position and composition of the individual dunes and the level of protection offered by the beach in front of them. Adding to this difficulty is the fact that most research on dune erosion has been conducted in scaled wave tanks or on the significantly different dunes of the northeast United States coast.

This study makes use of a robust data set that describes the near-shore waves and morphology. The goal of the study is to test a local adaptation of a wave-impact based model developed by Larson, et al. (2004) by hindcasting the erosion that took place at the Stilwell Hall site over the 2004-2005 Winter.

Several natural and artificial processes impact the type and rate of erosion along the Monterey Bay coastline. Primary among the naturally occurring morphology modes is the alteration of the beach profile caused by migrating rip currents. The impact of migratory rip channels, features that are observed throughout Monterey Bay and many other beaches worldwide, on the rate of dune erosion is examined. A feedback mechanism exists between the migratory rip currents and the development of mega-cusps, which are 10-30 m in width and 200-500 m in alongshore wavelength. Dune erosion is hypothesized to occur at the embayment of these large cusps (Short, 1979; Revell, et al., 2002). The beach is narrowest at the embayment, which facilitates interaction between the swash of storm waves and the dune face. This process accelerates undercutting, collapse of the dune and eventually, recession of the dune face and beach.

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# II. PREVIOUS STUDIES AND MODELING EFFORTS

Previous efforts to model dune erosion can be divided into two broad categories based upon the underlying theory employed. The first group is based upon older studies, which assume a conservation of sediment in the near-shore and are referred to as equilibrium profile models (Edelman, 1968). The second group, and the focus of most recent dune erosion study, is derived from wave impact theory (Fisher et al., 1986; Overton et al., 1987), which relates dune erosion to the assailing swash force on the dune face.

Equilibrium profile theory was developed by Edelman (1968) in an attempt to understand the effect of swash on beaches of very shallow slope in the Netherlands. This theory is based upon sediment conservation in the near-shore and assumes that "the eroded dune-sand beyond the breaker zone is not likely to occur" (Edelman, 1968). Implicit in the assumption of sediment conservation is the lack of any significant along-shore transport mechanism. It has been shown that there is indeed significant transport both off-shore and along shore at most beaches (Komar, 1998). According to this theory, as swash interacts with the dune, sediment is carried into the surf zone and deposited onto the bottom. Once the sediment transport is complete, the beach reaches a new equilibrium state and the dune face is shown to recede in order to replace the sand from the beach and dune that has been deposited in the surf zone. This approach relies on a cyclical process of erosion and subsequent deposition of sand in the nearshore, with no loss of local sand volume. This equilibrium profile response would instantly occur any time there is a sufficient rise in the sea-level, such as during a storm or exceedingly high tidal cycle, that the swash can impact the dune face. Various authors have discussed shortcomings inherent in this theory (Erikson, et al., 2005). A difficulty with the sediment conservation assumption is identifying the seaward extent of cross-shore transport, i.e. the seaward end of the equilibrium profile. The most significant limitation of this theory is assuming a near instantaneous beach response to any rise in sea level regardless of the duration of this change. It is apparent that the morphologic response of sand dunes due to swash inundation normally occurs on a slower time-scale than that of single storm surges and tidal fluctuation. Sand dunes vary in composition and resistance to scouring by swash

interaction, however all have some resistance to the erosion due to swash. As a result of the instantaneous response assumption, these models ignore this resistance to erosion and typically over-predict its effects (Fisher and Overton, 1984). The assumptions required by the equilibrium profile theory cannot be validated in the field, and therefore, limit the applicability of models derived from this theory.

The second approach applies physics based swash mechanics, dune composition and beach geometry. Collectively, models using this approach are considered based on wave impact theory. The initial theory was developed by Fisher and Overton (1984) and further refined by Nishi and Kraus (1996). The basic assumption is that the volume of dune erosion is the result of impact forces by individual waves. This theory was tested at the prototype-scale lab experiment during SUPERTANK, using two dramatically different dune profile data sets (Nishi and Kraus, 1996). The first was a low slope dune of un-compacted sand and the second of steeper, artificially compacted sand. The low slope, un-compacted sand case is similar to the dunes prevalent at beaches along the Northeastern United states while the compacted, steeper case is somewhat similar to the dunes around Monterey Bay.

Further work was done in developing an analytical model to predict dune recession by Larson et al. (2004). This model provides an analytical solution to the numerical model presented by Nishi and Kraus (1996) to predict dune erosion and includes a more refined approach to account for variations in dune composition. This model is adapted for use with the data set gathered in southern Monterey Bay and is employed in a predictive manner. The results indicate that that it is a suitable tool to predict dune erosion for future events.

# III. MODEL DEVELOPMENT

The theory presented follows the derivation by Larson, et al. (2004) and is based on the original assumption of wave impact theory by Fisher and Overton (1984). The basic assumption of the "wave impact theory" is that the weight of sand eroded, $\Delta W$ , is linearly related to the impact force, F, of the swash

$$\Delta W = C_E F \qquad (1)$$

where $C_E$ is an empirical coefficient accounting for the resistance of the dune to erosion. This weight can be calculated using the dune cross-sectional volume and composition to include sediment density and porosity, each of which can be measured.

The force of the impact for a single wave is related to the change in momentum as the swash bore impacts the dune given by

$$F_o = m_o \frac{du_o}{dt} \qquad (2)$$

where $m_o$ is the mass of the bore, $u_o$ is its speed and t, the time. The mass of the bore can be expressed as (Nishi and Kraus, 1996)

$$m_o = \frac{1}{2}\rho h_o s_o \qquad (3)$$

where ρ is the density of seawater, $h_o$ the wave height, and $s_o$, the length of the bore. The bore decelerates as (Nishi and Kraus, 1996)

$$\frac{du_o}{dt} \approx \frac{u_o}{T} \qquad (4)$$

where T is the wave period. According to linear wave theory

$$u_o = C_u \sqrt{g h_o} \qquad (5)$$

where $C_u$ is an empirical coefficient of O(1) (Miller, 1968). Inserting (3), (4) and (5) into (2) yields

$$F_o = \frac{1}{2}\rho u_o{}^2 h_o = \frac{1}{2}\rho \frac{u_o{}^4}{gC_u{}^2} \qquad (6)$$

Summing over the impact of many waves, during time Δt, the total force is given by

$$F = \frac{1}{2}\rho \frac{u_o{}^4}{gC_u{}^2}\frac{\Delta t}{T} \qquad (7)$$

Inserting the force equation into (1) and deriving an expression including the volume of the sand, ΔV, yields:

$$\Delta W = \Delta V \rho_s (1-p) g = \frac{1}{2} C_E \rho \frac{u_o{}^4}{gC_u{}^2}\frac{\Delta t}{T} \qquad (8)$$

where $\rho_s$ is the density of the sand, and p is the porosity. The analytical derivation by Larson, et al (2004) continues by re-arranging the previous equation, which yields an expression for the rate of dune erosion.

$$q_D = \frac{dV}{dt} = -\frac{1}{2}\frac{C_E}{C_u{}^2}\frac{\rho}{\rho_s}\frac{u_o{}^4}{g^2 T}\frac{1}{(1-p)} \qquad (9)$$

It is assumed that the bore decelerates due to gravity as it moves up the beach slope and that the additional effects of friction are negligible such that:

$$u_o{}^2 = u_s{}^2 - 2gz_o \qquad (10)$$

where $u_s$ is the initial speed of the bore as it starts to move up the foreshore slope and $z_o$ the elevation difference between the start of the swash zone and the dune face. To determine the speed of the bore at the dune face, it is assumed that it must be zero at the end of the runup, R. If $z_o$ is set to the runup height, (10) becomes

$$u_s{}^2 = 2gR \qquad (11)$$

Larson et al. (2004) assume a constant beach slope during the recession process to include the beach “under” the dune. Implicit in this assumption is that as the dune toe recedes, it gains in elevation above mean sea level (Figure 4). This assumption was not supported in the data acquired at the Stilwell Hall site where the dune toe receded at a

constant elevation (Figure 5). Therefore, in the model application here it is assumed that the toe elevation remains constant as the dune recedes and the beach slope is allowed to vary (Figure 6).

Holding the elevation of the dune toe constant, the dune face is assumed to recede at the angle of repose such that the dune toe and crest recede an equal distance. Using the previous expression for $u_o^2$ and substituting into the erosion equation yields:

$$\frac{dV}{dt} = -4C_s \frac{(R - z_o)^2}{T} \qquad (12)$$

where R is the run-up elevation and all the coefficients associated with the force of the swash and the dune composition are reduced to a single empirical coefficient, $C_s$,

$$C_s = \frac{1}{2}\frac{C_e}{C_u^{\,2}}\frac{\rho}{\rho_s}\frac{1}{(1-p)} \qquad (13)$$

The volume of dune erosion is given by

$$V = (D - z_o)\Delta x \Delta y \qquad (14)$$

where $\Delta x$ is the cross shore distance of the dune face recession, $\Delta y$ the alongshore width of dune being considered, D the height of the dune crest and $z_o$ the height of the dune toe. Both of the elevation variables are referenced to mean sea level (MSL). Applying the chain rule, the change in volume with time can be expressed

$$\frac{dV}{dt} = \frac{dV}{dx}\frac{dx}{dt} \qquad (15)$$

Differentiation of (14) yields an expression for change in volume per unit alongshore distance

$$\frac{dV}{dt} = (D - z_o)\frac{dx}{dt} \qquad (16)$$

This expression for change in volume with time can be equated to equation (12) and after some re-arranging an expression for the change in cross-shore position, or recession of the dune face, can be written as:

$$\Delta x = -4C_s \frac{(R - z_o)^2}{(D - z_o)} \frac{\Delta t}{T} \tag{17}$$

Equation (17) is used to predict the cross-shore recession of the dune toe. It is important to note that this model is only valid when the run-up height exceeds the elevation of the dune toe, $R>z_o$. If this condition is not met, there is no swash interaction with the dune. The model is tested against the data acquired at Stilwell hall in the next section.

# IV. DATA

The data set includes dune cross-sectional volume estimates derived from LIDAR imagery, near-shore wave climate estimates, local tidal data, beach profiles in front of the dune, periodic profile surveys of the dune toe and crest, soils analysis, rip channel timex imagery results and time-lapse photo imagery depicting migration of rip current channels. This data allows a field test for the wave impact theory based erosion model adapted from an earlier model by Larson et al., 2004. The analysis tests the hypothesis that erosion is accelerated at the embayment of mega-cusps caused by migration of rip currents (Short, 1979; Shih and Komar, 1984; Revell, et al., 2002).

The initial volume of beach and dune sand at this location was measured by an airborne LIDAR survey on 13 April 2004, shortly after removal of the sea-wall and prior to any erosion. The survey was conducted using an OPTECH 2050 altimeter from an altitude of 4000 ft and referenced to the NAD83 datum with 1m grid spacing and included the entire Southern portion of Monterey Bay from Moss Landing through Monterey. The LIDAR data are particularly useful in Monterey Bay due to the steep, nearly inaccessible dunes, which are normally too dangerous to survey using conventional ground based survey methods. The accuracy of the LIDAR data is better than 15 cm in the vertical with a horizontal resolution of 1-2m (Sallenger et al., 2000). In addition to the most recent LIDAR survey, surveys encompassing the El Nino winter of 1997 -1998 were available. These data were converted to cross-sectional volumes and the recession of the dune face at the Stillwell Site was determined. The 2m contour was overlaid onto the cross-section as well as the dune toe height which was approximately 4.6 m in elevation.

Directional wave spectra are operationally measured at the offshore NOAA buoy station 46042, which is located 27NM West of Monterey Bay. These spectra are refracted throughout the bay every four hours to the 10m contour using the O'Reilly CDIP refraction wave model. The spectra were then summed to calculate the significant wave height, $H_s$, wave period at the spectral peak, $T_r$, and mean wave direction (Figure 7).

Significant wave height is used as an input for the runup model to calculate the shoreward excursion of swash activity, which is then added to the tidal elevation to determine the occurrence of interaction between swash and the dune face.

Tidal data are continuously acquired and archived at the NOAA maintained CO-OPS data base, which is populated by the NOAA National Water Level Observation Network (NWLON), a buoy network covering most of North America. The tides within Monterey Bay are semi-diurnal in nature and tidal elevation is measured hourly at buoy 9413450, which is located in the bay (Figure 8). The semi-diurnal tidal elevation is added to the output of the runup model to calculate the uprush of swash onto the beach and possibly into the dune face.

The dune toe, 2m contour and beach slope were surveyed seven times between the removal of the seawall in April 2004 and February 2005 (Figure 9). The surveys were conducted using an all terrain vehicle (ATV) equipped with a kinematic GPS, which has a 5cm RMS error in all directions. The kinematic GPS receives and continuously processes a reference signal from a base station located at the Marina Water Conservation Authority Building, approximately 13km south of the Stillwell Hall site. The data were acquired as part of an on-going collection project at the Naval Post-Graduate School, which tracks the morphology of the coastline around Monterey Bay. The position of the 2m contour was determined from a two-pass riding survey performed using the ATV. The first pass is conducted near the water line and the second pass is higher on the beach. A 2m contour is interpolated assuming a constant beach slope between the two passes. The beach slope ($\beta_r$), between the two passes was also calculated and the output of an inclinometer mounted on the vehicle was recorded. The measured and derived beach slope values were compared and showed close agreement.

The raw output of the shoreline surveys was further processed to conform to a local datum, which is referenced to a six part composite idealized coastline for the 18km stretch of beach from the commercial wharf in Monterey, CA to the mouth of the Salinas River. This idealized coastline is a quadratic representation of the average coastline

position values and is particularly useful for examining cross shore recession and alongshore morphology since the position is expressed as an along-shore and cross-shore coordinate pair as well as an elevation value.

A photographic record of the entire California coastline is routinely created and maintained as part of the Coastal Records project. Oblique digital aerial photographs are taken at an altitude of 500 ft. Included with the image is a GPS position. In this library, several images of the Stilwell Hall area are available prior to demolition of the sea-wall, shortly after its removal and at the conclusion of time period evaluated (Figure 10). A downward looking aerial photograph covering the study site was also obtained. This photograph clearly shows the presence of rip current channels and the embayment of the mega cusps in the shoreline that characterize the area and affect the beach width dramatically (Figure 11).

Soil samples were acquired from several locations along the dune immediately in front of the study site. The samples were analyzed for porosity, density, grain size and compaction. The compaction varied dramatically along the dune due to the slumping of the dune face. The grain size varied through the sample with 96% of the sample ranging from 0.3 mm to 1.0 mm, with a mean grain size of 0.6mm (Table 1).

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# V. MODEL APPLICATION

The wave-impact based erosion model was tested by the comparing the dune toe recession measured from the seven surveys with model predictions. Part of the task of testing the erosion model was selecting a runup model to account for the interaction of the energetic winter wave climate and the relatively steep, narrow beach in front of Stilwell Hall.

The model is a 1-D line model and does not account for alongshore variability. To apply the model, the 150m long peninsula studied was divided into five 30 m sections (See Figures 9 and 12). Slumping, dune recession and mega-cusp migration were isolated within the five segments of the peninsula in order to examine them more closely. The correlation between rip channels and the associated meag-cusps was investigated to determine if they lead to increased erosion rates. Finally, sectioning of the peninsula mitigated the effects of the variability in the rate of erosion at its northern and southern terminus, which showed slower and more rapid rates,respectively.

A comparison of six runup models (Raubenheimer and Guza, 1996; Larson and Kraus, 1989; Hunt, 1959; Erikson, 2000; Mayer and Kriebel, 1994; Holman, 1986) was conducted in order to select the most appropriate model for this application. The input to the runup models include mean beach slope, significant wave height and wave period. The runup models were analyzed based upon the qualitative resemblance of the beach slope and wave data used in their development to that which exists at the Stilwell site. Most of the run-up models did not predict runup that would result in dune recession that is known to have occurred. The Larson and Kraus (1989) model was the only model that qualitatively gave runup resulting in dune erosion values that appeared appropriate. The outputs of Larson and Kraus (1989) and Raubenheimer and Guza (1996) models are added to the tide data to give the total runup. These total runup values were compared to the average toe elevation of the dune which was 4.6 m (Figure 13). When the height of the runup exceeded the dune toe elevation erosion of the dune occurred and was therefore switched on in the erosion model (Equation 17).

The rip currents prevalent in southern Monterey Bay create beach mega-cusps which, in effect, shorten the beach width and expose the dune to greater erosion (Thornton, et al., 2006). The scale of the mega-cusps, nominally 10-30 m in width and 200-500 m in alongshore wavelength, is significant relative to the size of area studied. However, the cumulative effects of these transient features can be absorbed through averaging of the 30m sections. In order to isolate and in turn analyze the cusps, the cross shore distance of the peninsula was taken as an average for each section (Figure 14). This position was the starting point for the model tuning.

The erosion model uses the output of the runup model to predict recession (Equation 17). The model is optimized by varying the empirical transport coefficient, $C_s$, to match the measured recession of the dune toe using the first and last survey positions. This coefficient is a function of the dune composition, its resistance to erosion and the wave energy that comes into contact with the dune. An optimal value for $C_s$ was calculated for each section (Table 2).

The model shows good agreement with the data acquired during the survey except in the case of slumping events (See for example Section 4, Figure 15). The model accounts for these events as part of the long term erosion process, but is not designed to predict them. Therefore,these single data points are overlooked in the long term analysis of model performance. The slumping events were easily identified in the aerial photo (Figure 16) and are identifiable in the surveys as approximately 10 m of seaward translation of the dune.

The volume of sand eroded from each section was then calculated (Table 3) so that a comparison could be conducted between the individual segments of dune. A time series of video images analyzed to determine rip channel location was then compared to the volume eroded in order to examine the effects of the beach cusp migration along the shoreline.

# VI. DISCUSSION

The impact theory based model developed by Larson, et al. (2004) was tested using field data acquired between April, 2004 and April, 2005 in the vicinity of the former Stilwell Hall site, Monterey, CA. This time period offered an extraordinary opportunity to study the effects of dune erosion due to swash inundation at a greatly accelerated rate compared with most beaches whose morphologic process are in pseudo-equilibrium and affected by only the coincidence of the most intense storms and high tides. Prior to the collection period, this site was protected by a rock sea-wall which was removed during the Stillwell Hall demolition process, which took place in March, 2004. The sea-wall artificially protected a large volume of sand from the normal erosion processes. After the rock-wall was removed, the beach fronting this peninsula was extremely narrow, increasing vulnerability to the effects of the active winter wave climate.

The 1-D, wave impact line erosion model requires an accurate description of the near- shore environment as well as the output of a runup model for application. Because of the dependence of the erosion model upon the underlying runup model, a literature review of the various models currently in use was conducted. During this review, particular emphasis was placed upon on the data used to drive the development of these models. The two models which seemed most suitable for use in the energetic winter season around Monterey Bay were developed based upon data collected for SBEACH (Larson and Kraus, 1989) and data collected off San Diego and San Onofre, CA during a series of experiments specifically conducted for the purpose of developing a runup model (Raubenheimer and Guza, 1996).

Further evaluation of the model developed by Raubenheimer and Guza (1996) initially indicated that it would be the most ideal for predicting the runup in Monterey Bay. It was selected for closer examination due to its heavy reliance on data collected solely in the field at a site with nearshore bathymetry somewhat similar to Monterey Bay. During the period of data collection, the two southern CA beach sites underwent very little morphology change with variations in slope less than .004. The San Diego site, at

which the data were collected during summer, was characterized by a very gently sloping, wide beach and the San Onofre Site, at which the data were collected at the onset of the winter season, had a narrower, steep beach. Of the two data sets, the data gathered at the San Onofre site more closely resembled the conditions at the Stilwell Hall site. The final model developed attempts to handle a variety of different beach types and wave climates by differentiating between beaches that can be classified as saturated and those that are reflective in nature (Raubenheimer and Guza, 1996). When this model was employed with the data collected during the 2004-2005 winter season in Monterey Bay, it appeared to under-predict the runup values owing to a lack to the calculated runup exceeding the dune toe, so that no erosion took place in contrast to the 11-12m of erosion observed (Figure 15). Anecdotal observations at Stilwell Hall, however, suggested a frequency of swash interaction with the dune on a weekly, if not more frequent, basis.

This problem of under-prediction may be due to the reflective nature of the beach surrounding Monterey Bay during this time. The data acquired by Raubenheimer and Guza (1996) indicated that the beaches studied in southern California were mostly saturated. With the narrower beaches and higher wave heights immediately in front of the dune studied here, the beach was highly reflective in nature. The model which they developed also lacks the ability to empirically adjust for the varying effects of friction on runup for beaches of different widths. Since the beach width immediately in front of the peninsula studied was extremely narrow, the effects of friction are considerably lower than those at either of the study sites in southern California. Finally, the significant change in beach slope in front of Stilwell Hall stands in stark contrast to the near constant beach slope at the southern California sites. The variability of the slope seen at Stilwell Hall is attributable to the migration of rip-channel induced mega-cusps during the period of evaluation, a process which accelerates the erosion process. Based upon the apparent systematic under-prediction of the run-up values by the Ruabenheimer and Guza (1996) model, it was determined to be unsuitable for application in this study.

The model developed by Larson and Kraus (1989) was empirically derived to match data measured in a large wave tank, and was developed based on the surf similarity parameter (Battjes, 1975). The output of this model, as well as that of the Ruabenheimer-Guza model (1996), was plotted over time and the dune toe elevation overlaid for

comparison (Figure 13). During time periods where the runup exceeds the dune toe elevation, interaction between the swash and dune face is predicted to occur; this interaction is the primary mechanism for dune erosion. The frequency with which the interaction is predicted by the Larson and Kraus model more closely resembles the description of the frequency of erosion events by the technicians who conducted the surveys at the Stilwell Hall site during the 2004-2005 winter. Some of the possible error sources in the runup model are mitigated to a certain degree empirically in the optimization process of the actual erosion model due to its dependence on the runup prediction. The results of the erosion model run suggests that the runup model adequately handles the wave climate at this study site by virtue of its success in predicting the dune recession (Figure 15).

In applying the 1-D line model, the peninsula in front of Stilwell Hall was divided into five, 30 m alongshore sections (Figure 9 and 12) to isolate various morphology processes. The five individual segments of the peninsula were averaged alongshore for each survey. Apparent in the seven surveys are three different morphology modes. The first is the shoreward recession of the dune, the primary focus of this modeling effort. The second is the presence of migratory beach cusps (Figure 16). These beach cusps dominate the entire Monterey Bay coastline and are associated with the rip currents (Thornton et al., 2006). The final morphology mode, which is seen in two of the seven surveys, is slumping of the dune face (Figure 14). This appears in the data collected during the surveys as an otherwise inexplicable nourishment and resultant seaward migration of the dune toe.

The model was then run for each section by tuning the empirical transport coefficient, $C_s$, to match the first and last survey data points, then the model in Equation 17 was run in a predictive mode using the entire data set of the seven surveys. A potential source of error in this tuning process is the possibility that either the start or end point of the surveys might coincide temporally with a slumping event. The combination of visual inspection of the progression of the cross-shore averaged surveys and the comparison of the derived coefficient for each section of interest to that of the other sections mitigated this possibility as a significant source of error.

The effect of the migratory beach cusps on the rate of erosion was considered. As a rip channel migrates along the coast, it creates a cusp embayment, which shortens the width of the beach. This is depicted in Figure 17 comparing the location of the mega-cusp embayment indicated by the 2m contour with the recession of the dune toe over time. This narrowing of the beach is normally accompanied by an increase in beach slope, the combination of which acts to significantly enhance the erosion potential. The decrease in beach width lessens the frictional effects of the beach on the swash energy thereby increasing the likelihood of interaction with the dune. The steeper beach slope causes a more reflective type beach profile on which the swash is directly tied to wave height.

Since the effects of this acceleration in the erosion process by mega-cusps are included in the survey averaging process, they were examined closer so their significance could be better quantified. As part of an ongoing project at the Naval Post-Graduate School, the location of rip channels is tracked using time-lapse photography images obtained from video cameras located 150m north of the Stilwell Hall site (Figure 18). Brightness minima in the image represents the relative lack of wave breaking activity which is expected in the deeper rip channel. During periods of rip channel migration, cusp migration normally lags rip location by 50m (Woods, 2005). The impact of this morphology process in any particular segment of the dune can be compared to that in the rest of the segments by comparing the amount of volume eroded in that segment. A higher volume eroded indicates a more rapid erosion rate.

During the initial period of the study, a rip channel migrated southward and then remained somewhat fixed in position (Figure 18). During the migratory period, it is expected that the cusp lags the rip channel by approximately 50m and once the migration of the feature stops that the cusp will adjust within about 15 days (Woods, 2005). While predicting the actual location of the cusp is quite difficult during the pauses in migration of the rip channel, it is assumed that after 15 days that the rip channel and beach cusp coincide. The location of the rip channel initially migrates from segment 4 southward to segment 2 during the period from early through mid-November. From mid-November through mid-January, the rip channel is located in segment 2. The rip channel then migrates rapidly northward to segment 5 where it remains from the end of January through the end of February.

Of the five segments analyzed, the first and last, on the ends of the peninsula, are oriented quite differently to the middle three during the period studied, so their susceptibility to the effects of the cuspate features is expected to vary as well. Segments 1 and 5 are most susceptible to 3-D effects of erosion, which are not handled by the model. Segments 1 and 5 are oriented obliquely to the coastline and the swash impacts the dune face at more of an angle than other locations. The first and fifth segments were not included in the results because of this. A closer inspection of the middle three segments reveals that segment 2 suffered a higher volume eroded than segments 3 and 4 (Table 1). This is attributed to the persistence of the rip channel and associated beach cusp in segment 2 during the period of investigation and suggests that the impact of migratory rip currents is significant.

The erosion model shows success in hind-casting the erosion events that occurred at the Stilwell Hall site over the 2004/2005. This success, which is based on locally 'tuned' values for $C_s$, does not necessarily make it generally applicable at other beach sites. If the model is to be used at other sites, the key to successful application lies in accurately determining a proper value of the empirical transport coefficient,which best captures the dune composition for the area of interest. The range of values calculated during the tuning process for the model in the middle three segments of the dune was $0.7 \times 10^{-3}$ to $1.3 \times 10^{-3}$. These values are similar to the results obtained from large wave tank data by Larson et al. (2004), who determined an optimal value for $C_s$ of $1.8 \times 10^{-3}$ and with 80% of the values ranging from $1.0 \times 10^{-3}$ to $2.5 \times 10^{-3}$.

The $C_s$ coefficient is ostensibly a measure of how the dune reacts to the assailing force of the swash (Larson, et al., 2004). The dunes along Monterey Bay are composed primarily of well-consolidated sand, are able to sustain a steep angle of repose and are relatively resistant to the impact of wave energy when compared with dunes of less stable composition. These dunes are also exceptionally tall which means that while the notching and slumping mechanism for erosion may be qualitatively similar to that of the northeast U.S. its slumping contributes significantly to damping the already relatively slow rate of the erosion due to slump-induced beach nourishment. After a slumping event, there is an artificial shielding of the dune face from further erosion due to the nourishment in front of the dune toe. This slows down or stops the erosion process of the actual dune until the

entire mass of slumped material is eroded. This slumping likely has an impact on the transport coefficient and its impact is directly proportional to the height of the dune. It would be useful to attempt to correlate the value of the transport coefficient to the height of dunes so that the likely effects of slumping could be included in the $C_s$ values.

Further work in determining the correlation between the empirical transport coefficient, $C_s$, and measured dune and surf characteristics should be pursued. The assumption of wave impact theory is that the eroded weight of sand is linearly related to the impact force of the swash, scaled by a dimensionless coefficient, $C_E$. Determining an appropriate value for this coefficient is difficult, but the dune properties which it characterizes are absorbed into the empirical tuning of the transport coefficient, $C_s$. The two coefficients are linearly related but not equal; $C_s$ includes a combination of $C_E$ and another dimensionless coefficient, $C_u$, that scales the dependence of the bore speed on the square root of gravity and offshore wave height (Larson, 2004) (Equation 5). Using the expression for $C_s$ presented by Larson (2004), which is shown in Equation 13, and assuming a mean porosity value of 0.35 (Holz and Kovacs, 1981), and an order 1 approximation for $C_u$ (Miller, 1968), it can be concluded that $C_s \approx 0.34C_E$.

# VII. CONCLUSION

Modeling sand dune erosion remains a difficult pursuit. Most of the studies attempting to describe the process have been conducted in wave tanks. Of the two primary theories available to describe dune erosion, wave impact theory appears to offer the most promise. According to the theory, the volume of sand eroded is directly proportional to the impact force of the wave driving the process.

The wave impact based dune erosion model developed by Larson, et al. (2004) was adapted and tested against a unique field data set for the winter of 2004-2005 in southern Monterey Bay, CA. This site was an old U.S. Army NCO club, which was removed due to the cross-shore recession of the beach in front of it. The data set employed was acquired after removal of a rock rubble seawall, which protected a large, artificially developed peninsula of sand approximately 150m in alongshore length. Upon removal of the seawall, the peninsula was more vulnerable to swash and therefore, the erosion process could be observed at a greatly accelerated rate.

Over the period studied, several morphology processes occurred. Primary among there processes was the migration of mega-cusps, which are erosional features of rip currents. The erosion rate of individual segments of the dune was enhanced at the embayment of these cusps where the beach is narrowest and steeper. The migration of rip currents and associated mega-cusps can be expected to accelerate the erosion of dunes.

The model is reliant upon accurate description of the runup of swash against the dune face, as well as the composition of the dune. The impact force of the swash is assumed linearly proportional to the volume of sand eroded through Cs. Using the data set gathered at the Stilwell site, the model was ‘tuned’ by adjusting Cs for each of the five, 30m alongshore dune segments. The Cs values ranged from .74x10-3 to 1.3x10-3 for the middle three segments. These values are comparable to values obtained by Larson et al. (2004). The optimal value he calculated in the large wave tank experiment for Cs was 1.8x10-3 with 80% of the values between 1.0x10-3 to 2.5x10-3.

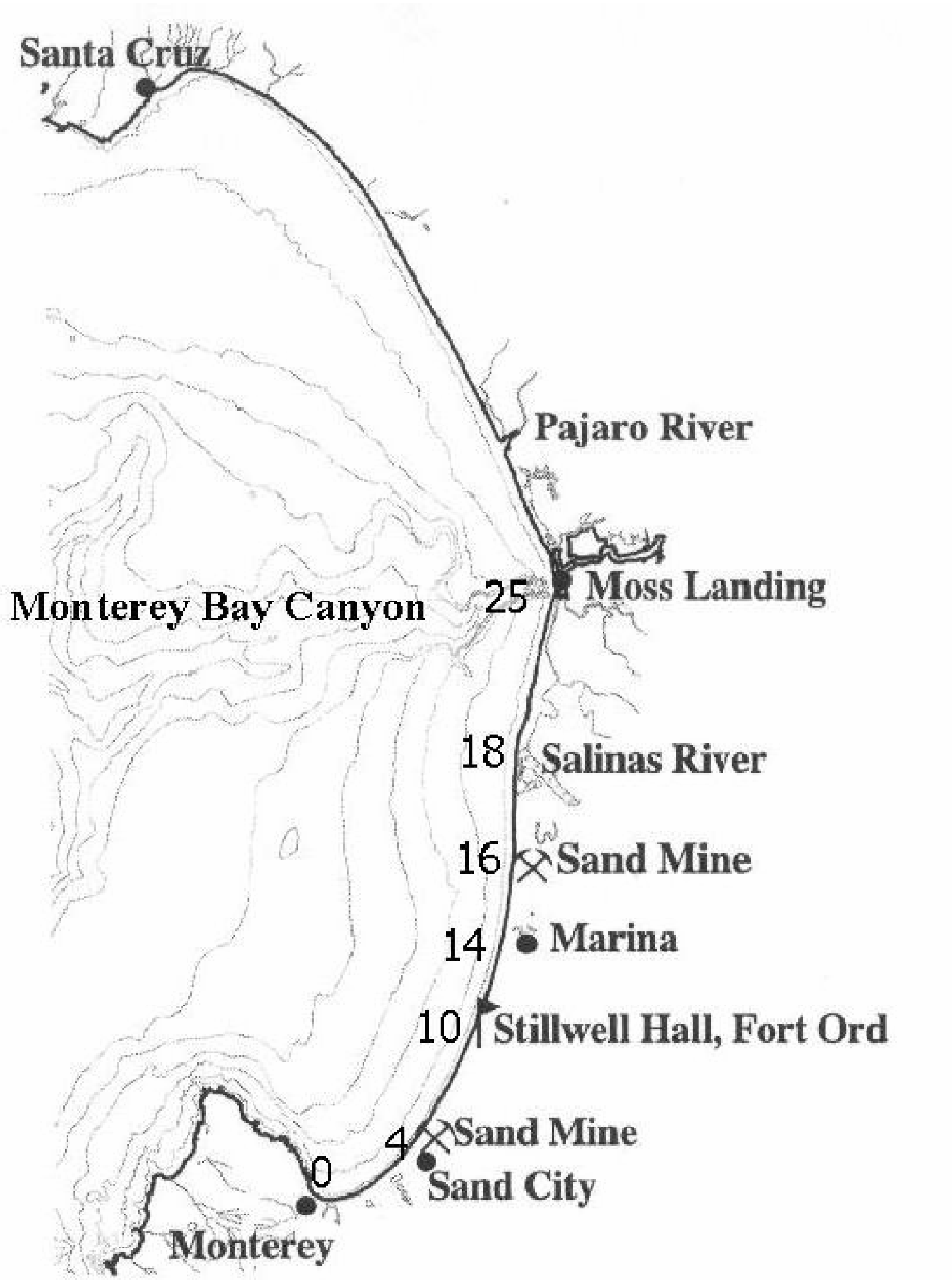


Figure 1. Map of Monterey Bay noting areas of particular interest including Stillwell Hall and the Monterey Canyon.


Figure 2. Photograph of the Stillwell Hall structure taken in 1950 while it still served as an enlisted NCO club on Fort Ord. This structure, along with a rock-rubble, which was later added to the beach in front of it, were demolished and removed in March 2004.

Figure 3. Photo of the Stillwell Hall site taken October 11, 2004 showing erosion of the peninsula on which the now demolished structure used to stand.

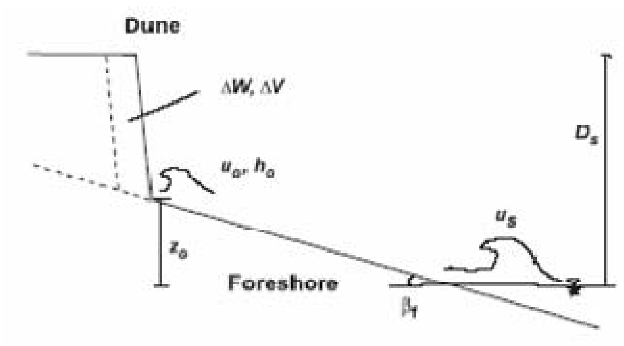


Figure 4. Schematic depicting the recession process of dunes as observed by Larson, et al. (2004) As seen here, during their study the dune was observed to move back and up along a constant foreshore slope resulting in a change in elevation of the dune toe.

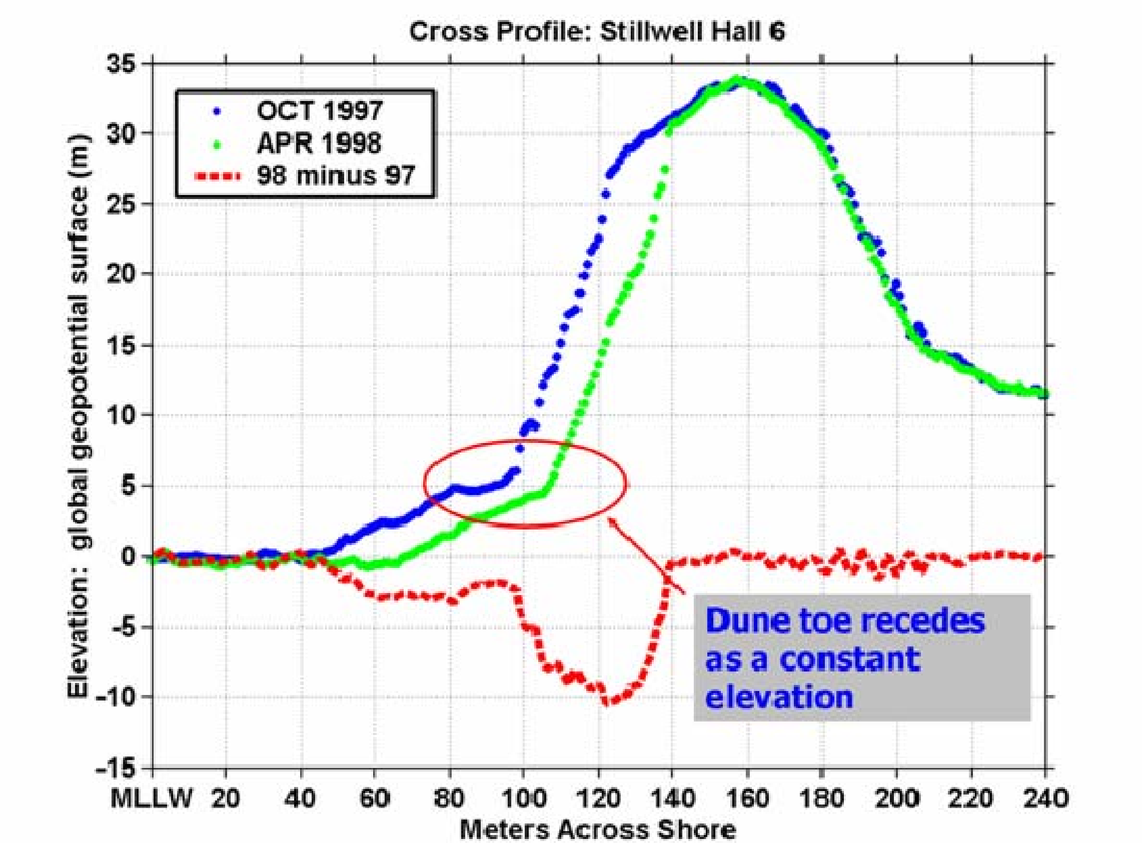


Figure 5. Plot of LIDAR data from 1997 and 1998 showing 9m cross shore recession at Stilwell Site during this El Nino winter. As seen here and evidenced by the ATV surveys, the dune toe recedes at a constant elevation.

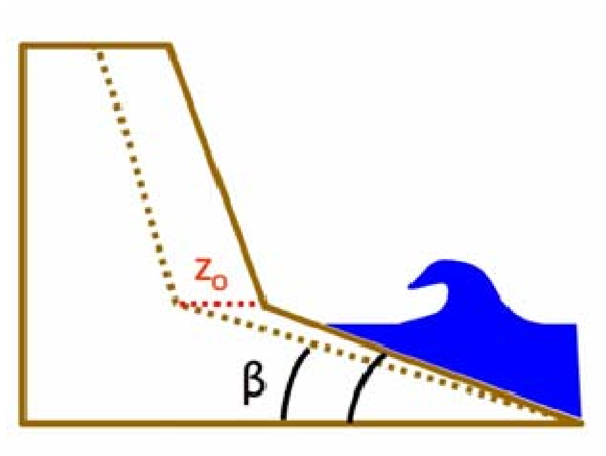


Figure 6. This diagram illustrates the decrease in steepness of the beach as the dune face recedes. The beach steepens, however, when the embayment of a mega-cusps migrated along the peninsula.

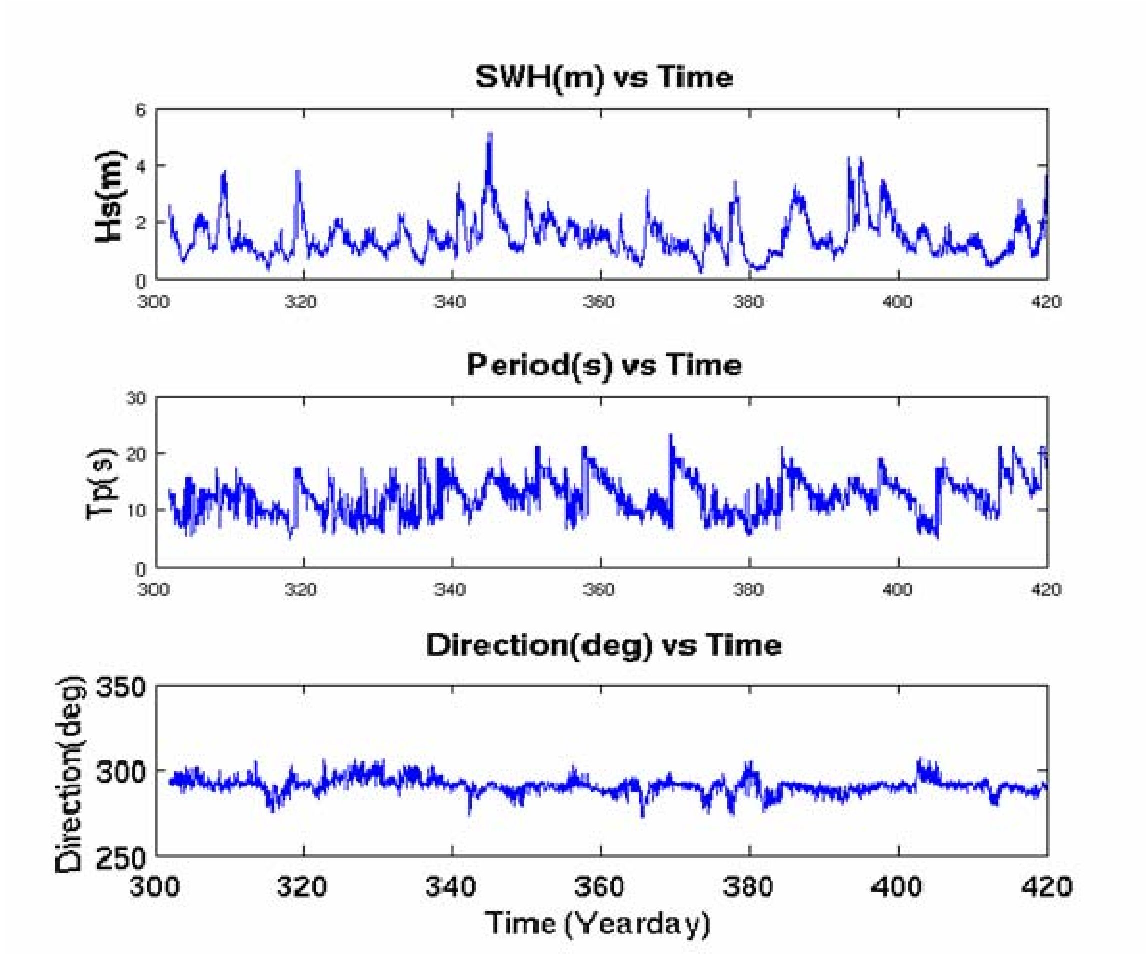


Figure 7. Significant wave height, wave direction and wave period as a function of time. The wave climate is output from the O'Rieley Surf Model at the 10m depth contour fronting Stilwell Hall.

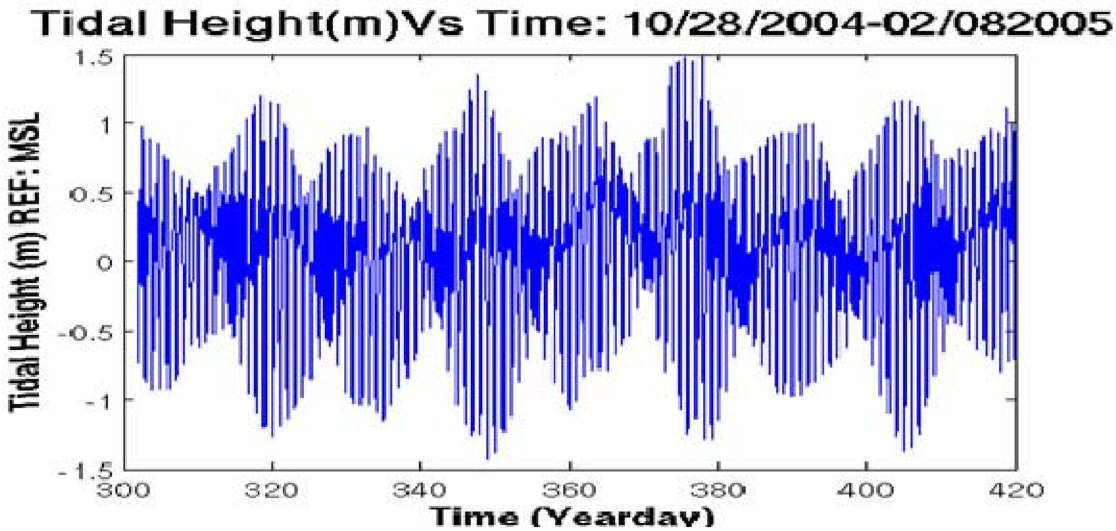


Figure 8. Tidal heights as recorded at the Monterey Buoy 9413450 located within Monterey Bay. Elevated high tide levels, such as those seen around yearday 370, are significant in determining the likelihood of interaction between swash and the dune face.

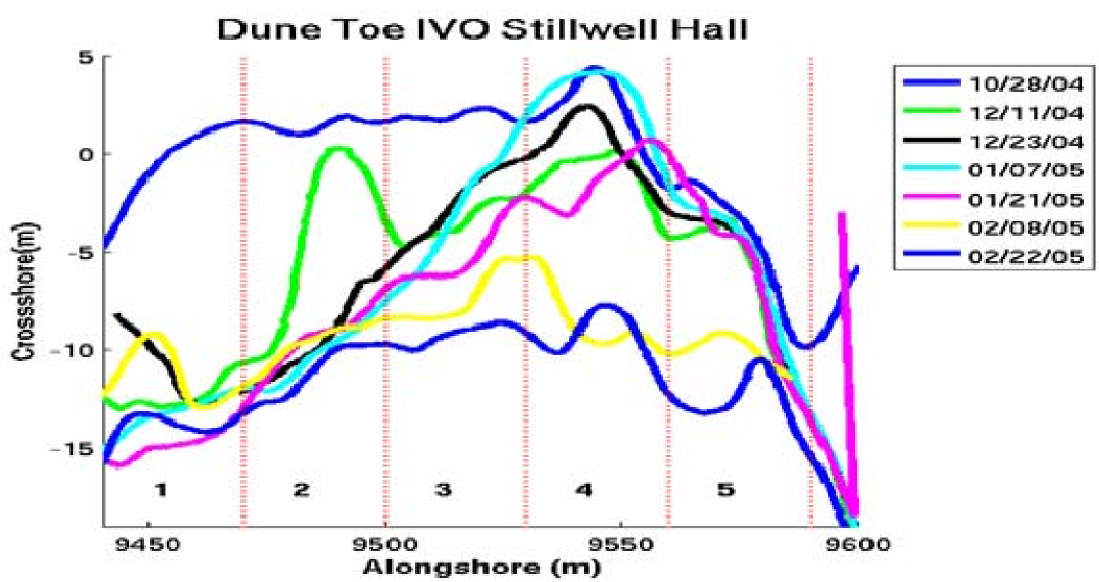


Figure 9. Output of the seven surveys conducted over the winter of 2004-2005 using along-shore and cross-shore coordinates. This coordinate system is particularly useful in tracking cross-shore dune recession. The area plotted is the peninsula that used to front Stilwell Hall prior to its demolition in March 2004. The five segments are shown which allowed for closer observation of the morphology.

Figure 10. Four aerial photos showing the Stilwell Site (August 2002, August 2003, October 2004, October 2005). The major feature of note is the peninsula formed by the sea-wall seen in the first two panels, but which is entirely eroded by the final panel.


Figure 11. Aerial Photograph of Stillwell Hall. The remainder of the peninsula upon which the Stilwell structure stood is visible. Rip channels are clearly seen as areas in the surf zone which are free of whitewater. The presence of these rip channels speeds the process of erosion.


Figure 12. Sand Peninsula, which was originally protected by the rock rubble sea-wall, showing the approaching swash. The segments on either end are nearly perpendicular to the rest of the dune which subjects them to 3-D effects that are not included in the model or described by wave impact theory. Because of this, these segments are ignored in the analysis of the model performance.

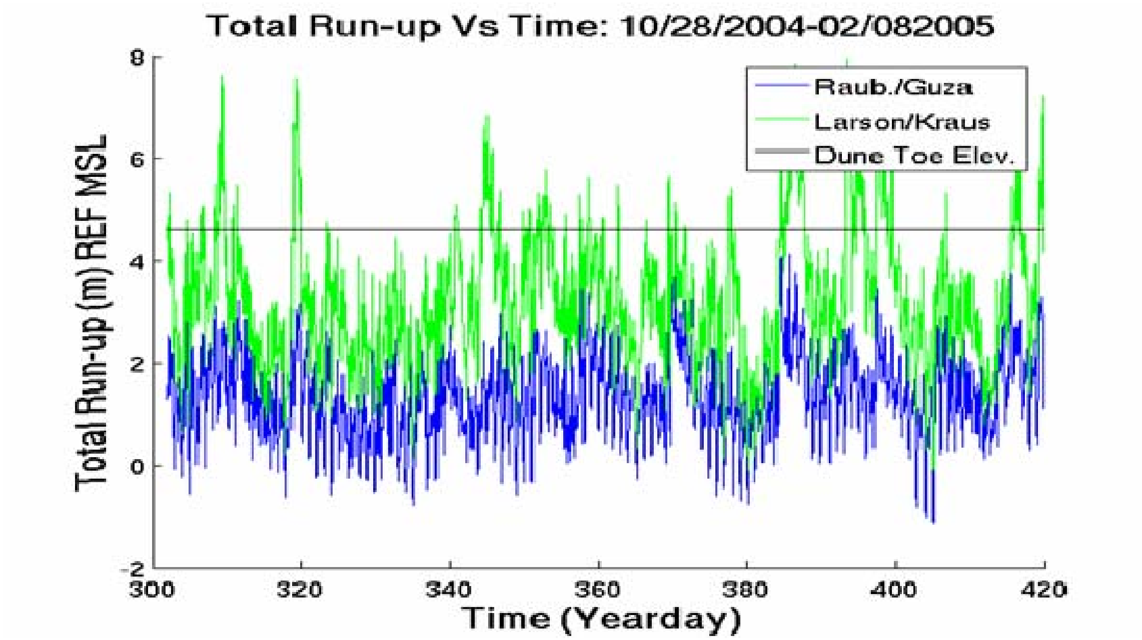


Figure 13. A comparison showing the output from two of the runup models evaluated (Larson & Kraus, 1989; Raubenheimer & Guza, 1996) after being added to the tide data to give the total runup at the dune toe. The difference in predicted runup, and therefore frequency of erosion events, highlights the significant difference between the various theories. The average dune toe elevation is also shown to illustrate the frequency with which erosion events took place.

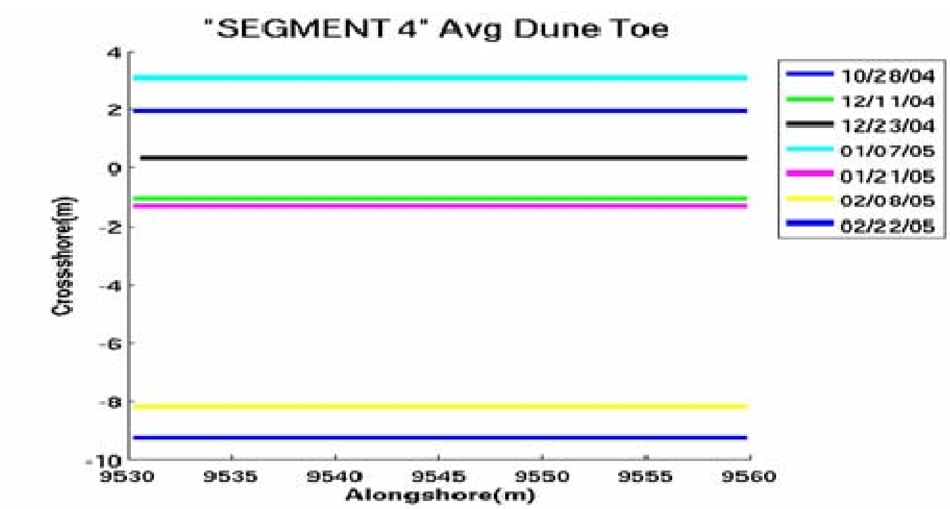


Figure 14. Plot of the average cross shore position of the dune toe for segment #4 which was used as the primary tool for tuning the empirical coefficient. This coefficient scales the model output for the local dune characteristics. This averaging was also used to evaluate the effects of rip current and beach cusp migration on erosion.

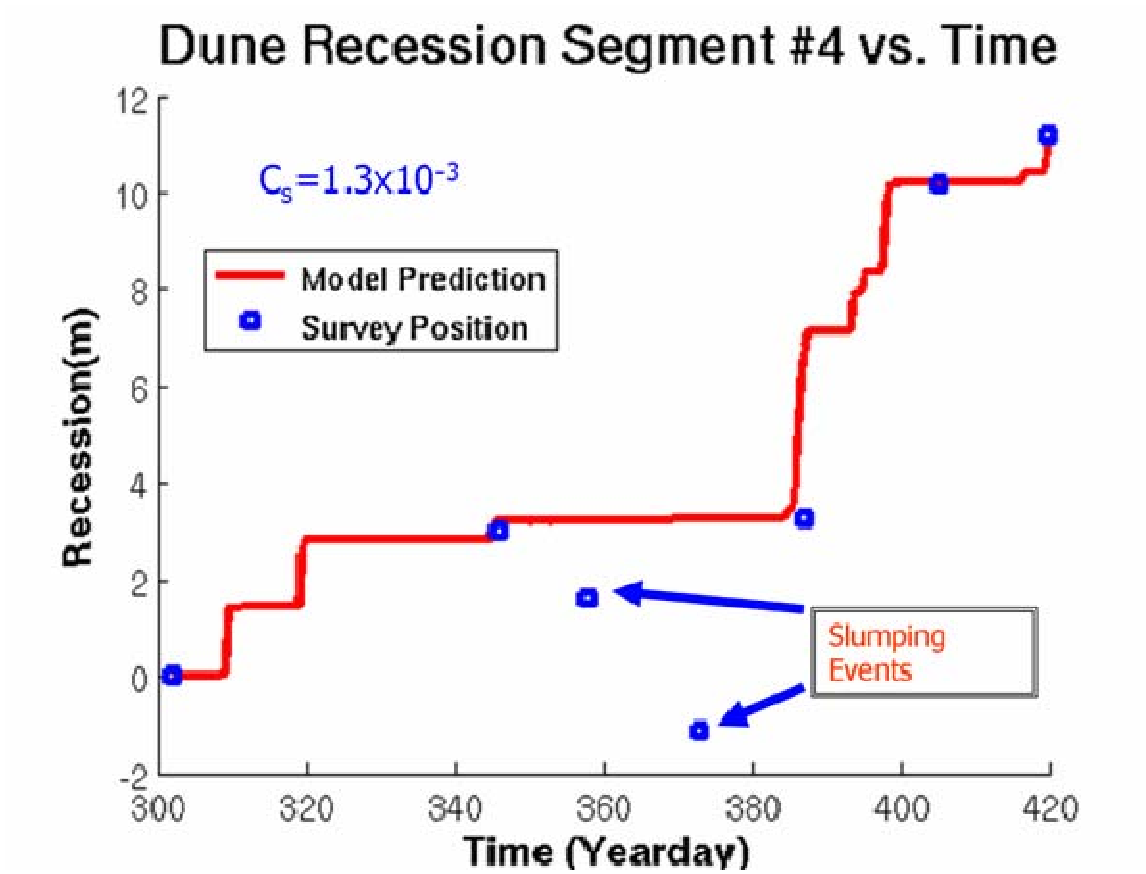


Figure 15. Output of the erosion model run on the segment #4 of the dune at the Stilwell Hall site obtained by tuning the $C_s$ coefficient using the first and last survey positions of the dune toe. The model output shows the predicted cross shore recession of the dune face and shows good agreement with the seven surveys conducted excepting the two slumping events, which are indicated.


Figure 16. Photo showing the effects of a slumping event on the profile of the dune face. These slumping events are not predicted by the model but the damping of the erosion rate caused by slumping events protecting the dune toe from wave energy is included in the long term prediction for recession of the dune toe.

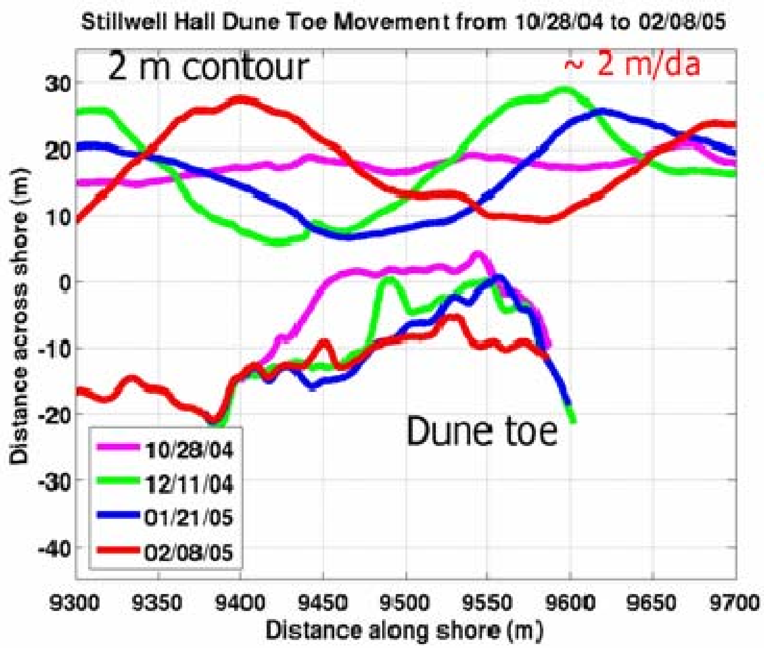


Figure 17. Figure depicting the migration of mega-cusps (2m contour) and the recession of the dune toe along the Stilwell Hall site between October 2004 and February 2005.

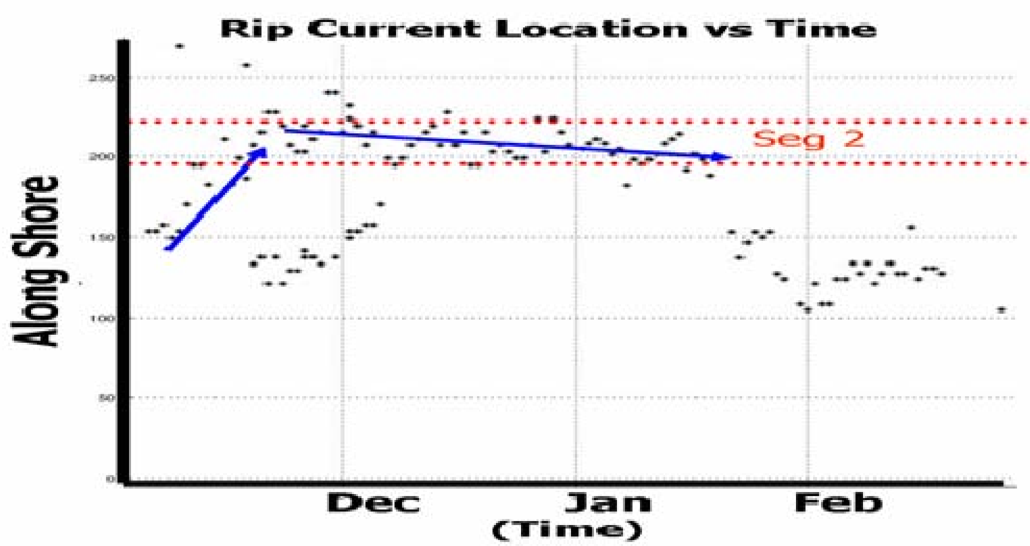


Figure 18. The migration of rip channels was tracked using time lapse photography (Woods, 2005; Minetree, 2006). Associated with the rip channels are mega-cusps, which develop along the beach. The cusps accelerate the erosion by creating a steeper, more reflective beach where the erosion is a function of wave height and the frictional effects on swash energy are significantly decreased. The rip channel dominated segment 2 during most of the period studied.

| Grain Size(mm) | % Distribution |
|---|---|
| 0.3 | 12.9 |
| 0.425 | 29.5 |
| 0.6 | 18.7 |
| 0.71 | 16.5 |
| .85 | 10.5 |
| 1.0 | 8.2 |

Table 1. Sand grain size distribution from Stilwell Hall site. The grain size varied in the sample with 96% of the sample ranging from 0.3mm to 1.0mm, with a mean grain size of 0.6mm

| | |
|---|---|
| Segment 1 | 0.6x10-3 |
| Segment 2 | 0.7x10-3 |
| Segment 3 | 0.8x10-3 |
| Segment 4 | 1.3x10-4 |
| Segment 5 | 4.4x10-4 |

Table 2. Values for the empirical transport coefficient, Cs, for each of the five segments of the dune. The values are in close agreement with the distribution of values calculated by Larson (2004).

| | |
|---|---|
| Segment 1 | 9748.5m^3 |
| Segment 2 | 9116.2m^3 |
| Segment 3 | 8045.3m^3 |
| Segment 4 | 8178.2m^3 |
| Segment 5 | 5550.1m^3 |

Table 3. Volume of sand eroded at the Stilwell Hall site, broken down by segment, between October 2004 and February 2005. Note that segments 1 and 5 are oriented nearly shore normally so the erosion mechanics are entirely different than those which exist at segments 2-4, which better portray the dune orientation prevalent throughout the bay.

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